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Strong electric fields from positive lightning strokes in the stratosphere

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[1] A balloon payload launched in Brazil has measured vector electric fields from lightning at least an order of magnitude larger than previously reported above 30 km in the stratosphere. During the flight hundreds of lightning events were recorded, including several positive cloud to ground lightning strokes. A two stroke flash, with small (15 kA peak current) and moderate (53 kA) positive strokes at a horizontal range of 34 km, produced field changes over 140 V/m at 34 km altitude. On-board optical lightning detection, recorded with GPS timing, coupled with ground based lightning location gives high time resolution for study of the electric field transient propagation. These measurements imply that lightning electric fields in the mesosphere over large thunderstorms may be much larger than previously measured. **Citation:** Holzworth, R. H., M. P. McCarthy, J. N. Thomas, J. Chin, T. M. Chinowsky, M. J. Taylor, and O. Pinto Jr. (2005), Strong electric fields from positive lightning strokes in the stratosphere, *Geophys. Res. Lett.*, *32*, L04809, doi:10.1029/2004GL021554.

1. Introduction

[2] As of this writing, no in-situ measurements of the electric field have been made over sprite producing thunderstorms in the altitude range of the sprite. Sprites are transient luminous events (TLEs) which were first imaged by Prof. Jack Winckler's group [*Franz et al.*, 1990], which occur between 40 and 90 km in altitude above thunderstorms correlated with positive CGs (cloud to ground strokes) [*Sentman et al.*, 1995; *Boeck et al.*, 1991; *Lyons*, 1994; *Boccippio et al.*, 1995]. These TLEs have been the subject of much research [cf. *Rodger*, 1999] and many theories as to the underlying physical mechanism [cf. *Pasko et al.*, 1995; *Lehtinen et al.*, 1997; *Fernsler and Rowland*, 1996]. However, the theories have generally required large electric field transients at 60 to 70 km altitude to produce sprites, while at the same time all the prior in-situ evidence from lightning-related electric fields in the middle atmosphere suggested that such large fields may not exist. That is, since the atmospheric conductivity exponentially increases with altitude [cf. *Hale*, 1984; *Holzworth et al.*, 1985], and since the largest reported lightning related electric fields in the mesosphere were in the range of tens of millivolts per meter [cf. *Siefring*, 1987; *Li*, 1993; *Barnum*, 1999], it was not clear that large electric pulses from lightning actually existed. These earlier rocket-borne measurements directly in the mesosphere over thunderstorms were, however, never over the really large storms which have often been associated with sprites [*Lyons*, 1996].

[3] It has been known for years that lightning transients, measured at hundreds of km horizontal distances at the Earth's surface, can be very large [cf. *Uman*, 1969]. We also had the evidence from electric field measurements directly inside thunderstorms [cf. *Marshall et al.*, 1995] and just over thunderstorms [*Blakeslee et al.*, 1989] that very large magnitude (kilovolt per meter) transients can be expected from lightning. However, much theoretical work had been done [*Dejnakarintra and Park*, 1974; *Holzworth and Chiu*, 1982] which suggested that the amplitude of the propagated lightning transient would decrease much too quickly in duration, and would likely be orders of magnitude too small at 70 km to cause a discharge. Indeed, even in the stratosphere most of the electric field data collected above 30 km altitude over thunderstorms, indicated field transients in the few V/m range [cf. *Bering et al.*, 1980; *Holzworth and Chiu*, 1982]. However, none of the earlier data were obtained over known sprite-producing storms, so the large pulses suggested by the sprite modelers remains a possibility [cf. *Pasko et al.*, 1997].

[4] In an attempt to obtain the needed in-situ measurements over sprite producing thunderstorms a new stratospheric balloon payload has been designed and flown. This payload included, among other instruments, 1) vector electric field measurements from dc to VLF and up to 195 V/m, 2) upward and downward looking X-ray measurements, 3) vector VLF magnetic field, and 4) an optical lightning detector. All the data were collected with a new 3 megabit per second digital telemetry system. During the balloon flight window of this experiment, we obtained some of the largest vector electric field measurements ever obtained over intense thunderstorms, and we also obtained images of sprites over Brazil, using ground based and airborne imagers, but we were unable to do both at the same time. That is, the vector fields we obtained from lightning were larger than anyone has reported at 34 km altitudes over such large thunderstorms, and they may well have caused red sprites, but we were unable to get the optical imager (which was mounted on an airplane at the time) out of the clouds to be able to simultaneously monitor the region of the mesosphere over the balloon. So, just as for the Sprites99 balloon campaign [*Bering et al.*, 2002] we did not get the data we desired. Nevertheless, the electric field data we did collect may provide a useful guide to sprite modelers, who have not had any in-situ data with which to compare directly with their models.

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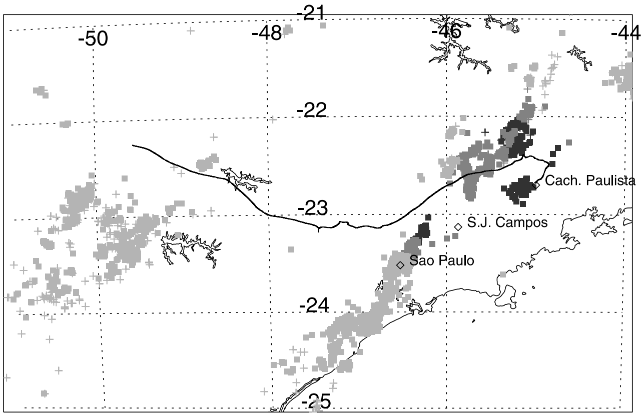

Figure 1. Balloon trajectory, along with lightning strokes (+ for positive CG, and boxes for − CG) recorded by the BIN Network within 50 km (darkest), 100 km or 150 km (lightest) of the balloon position.

[5] We will show examples of lightning related vector electric fields with total amplitude over an order of magnitude larger than previously reported using stratospheric balloon-borne electric field instruments. We obtained data from both positive and negative cloud-to-ground (CG) lightning, located by the Brazilian Integrated Network (BIN), which is an integration of three regional networks [*Pinto et al.*, 1999]. It is an hybrid network of 23 LPATS and IMPACT sensors (during this experiment) covering the Southeast region of Brazil and their borders. The largest positive lightning stroke during the flight had an estimated peak current of 53 kA, which is larger than the average peak current reported for sprites during a measuring campaign in Colorado [*Lyons*, 1996]. Furthermore, our data indicate that the electric fields had strong vertical and horizontal components, and durations somewhat longer than expected from the local relaxation time (independently measured by the conductivity sensor on the payload). Data from the optical imagers, magnetic search coils, and the X-ray instruments will be presented elsewhere.

2. Payload Instruments

[6] The balloon payload was very similar to earlier vector electric field experiments including detectors to measure the ac and dc vector electric field, optical lightning power time profile, positive and negative polar ion conductivity and external air temperature. Additionally, to search for the signature of energetic electrons from sprites, the payload included both up and down looking X-ray detectors. In addition to these instruments, all of which have been flown previously [e.g., *Holzworth*, 1977; *Holzworth and Bering*, 1998], this payload included a new electric field instrument to dramatically increase the range of the vector electric field detector [see *Thomas et al.*, 2004].

[7] The new electric field instrument is conceptually identical to the well known double Langmuir probe technique [*Mozer and Serlin*, 1969; *Holzworth*, 1977; *Holzworth and Bering*, 1998] but makes use of new, high voltage, low-leakage-current operational amplifiers (op amps). The instrument is described by *Thomas et al.* [2004]. Briefly these op amps [Apex PA141] were driven with new, high efficiency, isolated ±120 V power supplies. The probes for this instrument were 1.5″ × 8″ (4 cm × 20 cm) Aquadag coated, cylinders located part way out from the payload along the booms. Pairs of probes, with a separations of 1.6 m (vertical) and 2.0 m (horizontal), were mounted on orthogonal axes. The peak electric field detectable with this probe separation for the new instrument was close to a 200 V/m vector field. (This instrument could measure fields up to several kV/m with smaller probe separation).

2.1. Logistics

[8] The balloon flight was launched December 6, 2002 at 2200 UT from Cachoeira Paulista, Brazil (22°44′S, 44°56′W) ahead of an approaching line of thunderstorms. Figure 1 shows the flight trajectory (solid line) and the lightning events within 50, 100 and 150 km of the trajectory (+ signs and boxes shaded darkest (closest) to lightest (farthest), respectively). The balloon headed northeast after launch, until it reached the stratosphere, where it turned westward, and a little south. The balloon was a 300,000 cu ft Raven 0.35 mil polyethylene bag, which achieved a float altitude of 34 km, where it remained relatively stably. The payload encountered thunderstorm fields essentially from launch through about 0300 UT. The flight terminated after 1000 UT Dec 7, 2002. The lightning stroke timing and location data shown in Figure 1 come from the BIN lightning network [*Pinto et al.*, 1999].

2.2. Electric Fields

[9] Figure 2 presents a sample 80 minute period of the vertical electric field, on the waning side of the first storm encountered during the flight. Here we see a slowly decreasing dc field from 50 V/m down to near zero, and many lightning transients. Most of these lightning events were detected by the network as positive or negative CGs (Cloud-to-Ground strokes). The largest pulse in Figure 2 occurred at 00:00:09UT, had a peak current of +53 kA and was caused by a lightning stroke located at a horizontal distance from the balloon of 34.4 km. It is also interesting to note that for this entire 80 minute plot the positive strokes (downward spikes in the electric field) are larger than the negative strokes. This feature holds true for the entire flight.

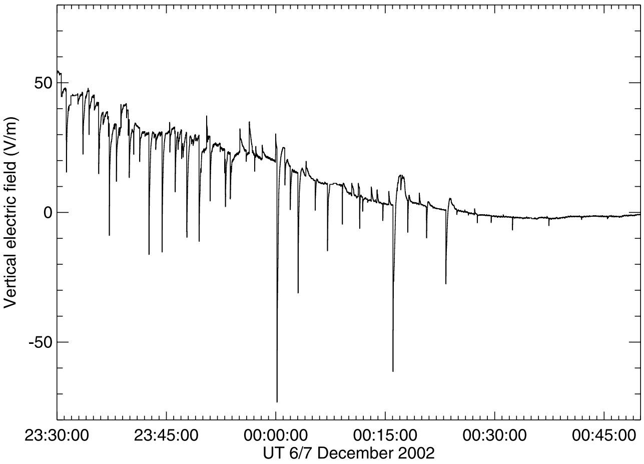

Figure 2. Vertical electric field measurements. Note strong negative transient near 00:00 UT which is related to a 53 kA positive CG.

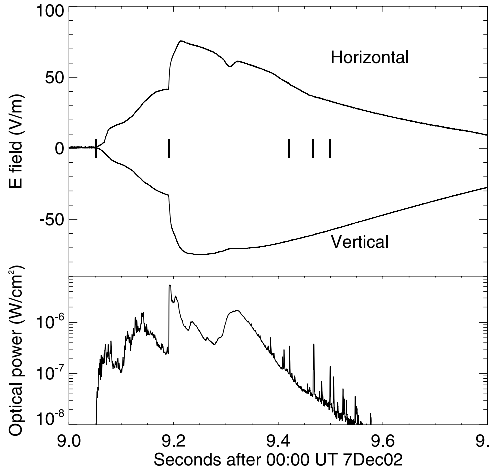

Figure 3. Electric field and optical power during the large positive CG identified in Figure 2. The ac electric field detector has a 1s roll off (high pass) filter, so the decay is artificially fast compared to the dc data. Five vertical marks in the top panel correspond to sharp transients in the optical power time profile (bottom panel).

[10] *Thomas et al.* [2004] presented an expanded view of the dc electric field components from this largest positive CG stroke just after 00 UT (identified in Figure 2 as 53 kA). Thomas et al showed that the electric field had approximately equal horizontal and vertical components, and a decay time which extended for many seconds at this altitude of 34 km.

[11] To observe the fast electric field changes of this same stroke, in Figure 3 we show the ac electric fields and optical light for the same 53 kA event (as identified in Figure 2). Here in Figure 3 we see that the electric field begins to increase slowly as soon as the first optical variations are detected, and achieves a magnitude of about 42 V/m (horizontal) and 37 V/m (vertical) just before the main lightning impulse at about 9.2 s, after which the fields achieve their maxima. Note that the first two vertical dashed lines in Figure 3 refer to the time of a 15 kA and the 53 kA positive strokes, respectively. So this event is characterized by having a second (larger) stroke occur while the fields are still elevated after the first (smaller) stroke. The time between these two strokes was about 140 ms, which is much shorter than the local relaxation at the balloon payload, and thus the fields add together to produce a net field of over 140 V/m (root mean square of the DC vertical and horizontal fields, as shown in detail by *Thomas et al.* [2004]).

[12] The conductivity was also measured on this flight using the relaxation technique [*Holzworth and Bering*, 1998]. The low voltage vertical probes were momentarily biased with + or −2.5 V, and allowed to refloat. The decay time to ambient field levels gives a nearly direct measure of the conductivity [see *Holzworth et al.*, 1986]. Each decay curve was individually inspected to be sure it is not perturbed by a simultaneous lightning stroke. The new high voltage probes were not biased and were not used for making conductivity measurements. Therefore conductivity measurements are only available when the low voltage probes were not saturated, that is, after 0010 UT. Figure 4 shows a sampling of one conductivity point every 10 min (both polarities) for 8 hours. Each point is derived from the high time resolution telemetry data, which includes hundreds of data points in each decay profile, resulting in excellent exponential fits to determine the decay time constants. The error in this fitting process results in error bars which are about the size of the point symbols in Figure 4, where we see that the polar components of conductivity (+ and − signs) have magnitudes of about 3.5×10^{-12} S/m, while the total conductivity is twice this value (solid line).

[13] The conductivity is disturbed until about 0320 UT, including a time near 0230 in which both polar components are about a factor of two lower than the ambient conductivity. Note that the electric fields and lightning activity peaked again at about this time (0200 to 0230 UT).

3. Analysis and Discussion

[14] As mentioned in the introduction, we were unable to make low light level images of any sprites that may have occurred in and above the vicinity of the balloon because severe weather restricted the operation of the observing airplane (which was carrying the cameras). So we do not know if any of these large lightning transients produced sprites. However, the electric field levels we observed were more than an order of magnitude larger than we have measured previously at this altitude (over 30 km) and might have been important for TLE production.

[15] It is useful to discuss the possible relationship between the large fields reported here, and the peak fields that might be expected at altitudes where sprites have been seen (between 35 and 90 km from bottom of the tendrils to the top of the sprite [cf. *Lyons*, 1996, although we note that a rare example or two of sprites producing visible light from the cloud tops to the ionosphere have now been published [*Pasko et al.*, 2002; *Su et al.*, 2003]. There are both time dependent and geometric aspects to mapping electric fields in one region of the atmosphere to another. A Green function approach to the propagation was discussed by *Holzworth and Chiu* [1982] and a full wave calculation was done by *Baginski et al.* [1988]. These generally agree within a factor of two in time with the simple model by *Greifinger and Greifinger* [1976] involving the concept of a moving parallel plate capacitor.

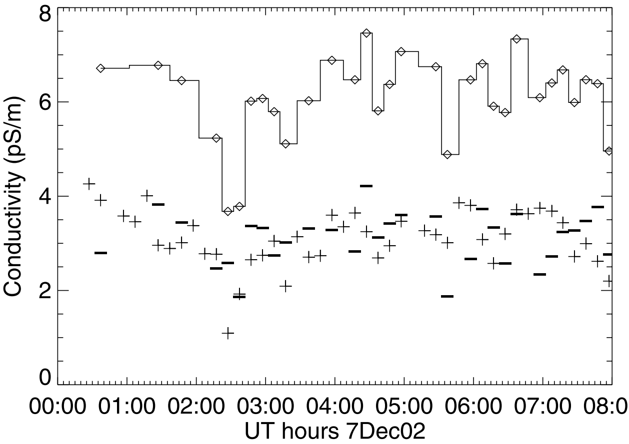

Figure 4. Polar (+ and − signs) and total (solid line) electrical conductivity for 8 hours on 7 December 2002.

[16] The amplitude of the dipole electric field generated by a monopole charge (the lightning charge removed from the cloud) and its mirror charge (since the ground is an excellent conductor), will decrease with distance as $1/r^3$. However, if the cloud charge involved in the parent stroke is initially spread over a horizontal radius on the order of the distance between the cloud and the ionosphere (say 50 to 100 km) then the electric field above such an extended thundercloud charge may have very limited dependence on r, similar to what we expect for a parallel plate capacitor. The thunderstorm clouds seen during this experiment, as well as that of many other sprite experiments, were horizontally extended for several tens of kilometers. Therefore, without knowing the exact charge distribution and doing a full model, we suggest that the actual field distribution immediately after the lightning (and before the time of the local relaxation at the highest altitude) may have had a dependence on the distance r which was intermediate between a that of a dipole and that of a parallel plate capacitor. In such a case, the field we measured at 34.4 km from the lightning may be closely related to that at 50 to 70 km over the storm, where we might expect a sprite to be initiated. That is, depending on the geometry of the charge distribution, the field at 50 to 70 km altitude may also have been within an order of magnitude of the fields measured at the location of the balloon (as opposed to the decrease expected of $1/r^3$ for a dipole charge distribution).

[17] Another important consideration is related to the conductivity. If the local time constant at 60 to 70 km where sprites initiate, is long enough, then the electric field from the two lightning events shown in Figure 4 will add, just as they do in the stratosphere. We did not measure the conductivity profile, so we cannot extrapolate a value for the local relaxation time up to sprite initiation altitudes from our single-altitude data set. But, we can make the suggestion that the time constant may be longer than usual at 60 to 70 km. Using the only published conductivity profile from the stratosphere all the way to the ionosphere over a thunderstorm [see *Holzworth et al.*, 1985], which has an exponential scale height of 11 km between 30 and 60 km altitudes over a thunderstorm, we might expect that the time constant at 60 km was about 200 ms or more. In fact the conductivity at the balloon from Figure 4 above is about a factor of two smaller than the conductivity at the same altitude in the profile of the earlier work [*Holzworth et al.*, 1985]. Using the conductivity profile they present from 1985 rocket and balloon data, but shifted to lower values so the profile matches the lower conductivity over this Brazilian storm (keeping the scale height the same), results in a conductivity at 65 km of about 10^{-10} S/m. This represents a time constant near $8.85 \times 10^{-12}/6 \times 10^{-11} \approx 0.147$ s = 147 ms.

[18] If the local relaxation time constant at sprite initiating altitudes is 100 to 200 ms, then the two lightning transients identified in Figure 4 will add, making a total field larger than either single event (just as they add at the balloon altitudes).

[19] So our speculation from mapping the measured electric field is that we could find fields of 100 V/m lasting 0.1 s at 60 km altitude. This is long enough to give sprites plenty of time to develop.

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